RADIATION PHYSICS NOTE 91

CHARACTERIZATION OF THE NEUTRON FIELD IN THE ANTI-PROTON TARGET AREA AND IN THE LINAC TUNNEL

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I. INTRODUCTION

In this note we present the results of some preliminary attempts at characterizing the neutron radiation field in two Accelerator Division areas: In the Linac tunnel near tank 5 just downstream of where the beam is bent to NTF, and over the $\overline{P}$ target vault (APØ).

II. EXPERIMENTAL SETUP AND ANALYSIS

At both locations, a Bonner multisphere spectrometer was used to determine the neutron spectrum. This technique has been discussed many times previously (1). In the present measurements TLD 600's (^{6}LiF, enriched to 95.6% ^{6}Li) and TLD 700's (^{7}LiF), in stacks of 4 chips each, were placed at the center of moderating polyethylene spheres having diameters from 5.08 cm to 45.7 cm, one set with no moderation (bare detector) was also used. Both the ^{6}LiF and ^{7}LiF chips respond equally to photons and charged particles while the ^{6}LiF chips are much more sensitive to thermal neutrons (through the ^{6}Li(n,α)^{3}H reaction). Thus, the neutron response of the TLD 600 was obtained by subtracting the photon/charged particle contribution given by the TLD 700 response. Both sets of TLD's were calibrated for gamma response by use of a ^{137}Cs radioactive source. An appropriate neutron calibration entails measurement of the response of each sphere in a neutron field, say, e.g., an AmBe neutron source. In the present case this was not done. Instead each TLD was exposed as a bare chip to an AmBe source. This allowed for a correction for individual differences in chip response to neutrons, but not to convert charge from the TLD readout into neutron fluence. It was not possible therefore to measure true fluence, dose, or dose equivalent. Even so, useful information concerning the properties of the radiation field could be obtained and is discussed below. In the measurement at both locations film badges placed on either end, and in the middle of the Bonner Sphere array, were used in an attempt to determine the uniformity of the radiation field during the exposure of the TLD chips in the spheres.

To unfold or deconvolute the spectrum from the Bonner sphere measurements, two well known computer codes were used, BUNKI (2) and LOUHI (3). BUNKI is a code based on an iterative recursion method, while LOUHI is based on a non-linear least square method with user controlled constraint conditions. It is useful to use two codes to gain confidence in the results of the unfolding, because of inherent difficulties of the unfolding problem due mainly to its undetermined nature. That is, since there are eight detectors and generally thirty-one energy groups one is left with the need to solve eight equations for thirty-one unknowns. In all codes, the response functions of Sanna (4), calculated for 4 mm by 4 mm ^{6}Li detectors, were used as a good approximation to the ^{6}LiF TLD 600 responses.

At the location in the Linac Tunnel, a recombination chamber (5) was used to determine the quality factor of the total radiation field independent of its determination in the Bonner Sphere measurements. The procedure has been described previously (6). In the present situation, however, there was insufficient beam time to allow the response of the ion chamber to be determined over the full operating range of voltages from -20V to -1200V. Instead measurements were performed at only two voltages -65V and -1200V and the quality factor determined (see ref. 5) from the equation below

$$Q=25\left(1-\frac{q_{-65}}{q_{-1200}}\right) \tag{1}$$

The response of the chamber at the two voltages (-65V and -1200V) was normalized to that of a tissue equivalent ion chamber (Chipmunk) placed adjacent to it in order to compensate for any non-uniformity in the radiation field.

III. THE AP0 TARGET VAULT

Figure 1 shows the Bonner Sphere set up in the area above the anti-proton target vault. This area is shielded from the target by 2 meters of steel followed by covers of polyethylene beads and borax. Film badges that contain gamma-ray film and Lexan (polycarbonate) neutron detectors were positioned near the spheres as indicated. After exposure, gamma ray doses were found to be considerably greater than the neutron doses (about a factor of ten), in agreement with previous measurements (7) in this region. Further, the Lexan results showed that the neutron flux was uniform over the Bonner Sphere array.

Two independent measurements - separated by a two day interval - were made. Sphere response as a function of diameter is shown in Figure 2, compared with the results from spectrum unfolding with the BUNKI code. Although not indicated on Fig. 2, the experimental uncertainty associated with the measurement is 15-30%. These large values arise because of the very large background on the TLD 600 chips due to the high gamma ray doses in this location.

Figure 3 shows the spectrum from the first run (29/8/90) unfolded from the measured sphere responses by use of both LOUHI and BUNKI codes. The ordinate for the lower curve represents fluence per unit energy interval. In such a representation many of the finer details of the neutron spectrum are suppressed. In the upper curve, on the other hand, which shows fluence per unit lethargy (or per unit logarithmic energy interval), the energy dependence is suppressed and spectral details are enhanced. Further the area under the curve for each energy bin is proportional to the neutron fluence within that bin.

As observed in Fig. 3, the gross features of the neutron spectrum unfolded with both codes are in approximate agreement, lending some confidence to the reasonableness of the solutions. Even so because of the finer details in the spectrum the results from LOUHI suggest a considerably larger percentage of total fluence associated with neutrons of energy greater than 2 MeV than does BUNKI. However, the percentage of dose equivalent associated with such neutrons is about the same for the two codes, as is the Quality Factor of the neutron field. These results are represented in Table I.

For the second run (31/8/90), shown in Fig. 4, even the gross features of the observed spectra from both unfolding codes are in considerable disagreement at energies above 1 MeV. This suggests that any conclusions concerning the high energy neutron contribution should be viewed with some skepticism. As seen in Table II, even the QF's tend to disagree. It should be noted that, in general, the 18" sphere is not an ideal detector for neutrons with energies greater than 20-50 MeV. A detector based on the activation of carbon (through the $^{12}C(n,2n)^{11}C$ nuclear reaction) is, e.g., considerably more sensitive to neutrons with energies over 20 MeV.

As mentioned above, film badge measurements at the location of the Bonner Sphere array showed that the gamma ray dose equivalent is about a factor of ten higher than that due to neutrons. In fact, about 90% of the total dose is due to gamma rays. Since the quality factor for high-energy photons is unity, and assuming a neutron quality factor from Table I of 5.8 then the average quality factor in the combined field can be found as $\overline{QF} = 0.91 \times 1 + .09 \times 5.8 = 1.43$. This value is in reasonable agreement (about 15% high) with a previous measurement in the same area of 1.23 (7).

In summary, based on the above discussion, the detailed properties of the neutron field in the area above the APØ target vault should be viewed as somewhat uncertain, particularly at energies above a few MeV. We observe, however, in spite of such uncertainties, that while only 20-30% of the fluence arises from neutrons with energies greater than 2 MeV such neutrons account for more than 80% of the dose equivalent. Ignoring the LOUHI results on 31/8/90, the average quality factor of the neutron radiation field is 5.8.

IV. THE LINAC

The measurements performed in the Linac vault near Tank 5, downstream of the dipole that bends the beam into the Neutron Therapy Facility (Fig. 5), was limited to a total dose of about 300 mrem as recorded on a Chipmunk hung from the wall near the Bonner Sphere array. In this short time interval the neutron Lexan badges spaced between the spheres as indicated in Fig. 5 received only a minimum exposure so that it wasn't possible to determine the uniformity of the flux over the array. Furthermore, the TLD's within the spheres received a relatively small dose as well, so that the results described below represent only a preliminary determination of the properties of the radiation field.

Figure 6 shows the measured sphere responses compared to those based on unfolding with BUNKI. The unfolded spectrum itself is shown in Fig. 7. Both BUNKI and LOUHI display the same spectral features, even to an indication of a small contribution from neutrons with energies greater than 200 MeV. A recalculation with LOUHI in which the fluence is constrained to be zero at energies above the proton beam energy, as is physically reasonable, gave a much worse fit. Again, therefore, as with the results at the APØ target vault, the details of the neutron spectrum at energies above a few MeV should be viewed as uncertain. In Table III the properties of the neutron radiation field, as obtained with both BUNKI and LOUHI, are compared. About 80-90% of the fluence arises from neutrons with energies below 100 keV, but 50-60% of the dose equivalent comes from those of higher energy.

The Quality Factor of the neutron field has a value of 4 from both codes. On the other hand the Quality Factor of the average radiation field has been determined to be about 6 from the recombination chamber measurement. These two values are inconsistent with each other if the radiation field consists only of neutrons (Q=4) and photons(Q=1). If on the other hand the recombination chamber is sensitive to charged particles (with Q substantially greater than 1) and if such particles represent a sizable contribution to the field, the two values might be reconciled. We currently, however, have no knowledge of the properties of the charged particle contribution to the average radiation field.

To summarize: The general properties of the radiation field are specified in Table III. The fluence of neutrons above a few MeV is uncertain; the unfolded spectrum reflects the existence of a small number of unreasonably high energy neutrons. Finally, the reconciliation of the two QF measurements relies on the unknown contribution of charged particles to the radiation field in the Linac tunnel, and on the unknown response of the recombination chamber to them.

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7. P.M. Yurista, A.J. Elwyn, "Some Characteristics of the Radiation Field over the $\overline{\mathrm{P}}$ Target Vault," Fermilab, Radiation Physics Note 73, 1988.

FIGURE CAPTIONS

Figure 1	Anti-Proton Target Building (APØ).
Figure 2	Sphere Responses as a function of diameter, (APØ) run, measured results are compared with the one from spectrum unfolding using BUNKI code.
Figure 3	Unfolded spectrum, run 29/8/90 (APØ), from the measured sphere responses by use of both LOUHI and BUNKI.
Figure 4	Unfolded spectrum, run 31/8/90 (APØ), from the measured sphere responses by use of both LOUHI and BUNKI.
Figure 5	The Bonner Sphere set up at the Linac Tunnel.
Figure 6	Measured sphere responses compared to those based on unfolding with BUNKI code, in the Linac tunnel.
Figure 7	The unfolded spectrum, from the measured sphere responses by use of both LOUHI and BUNKI, in the Linac tunnel.

TABLES

Table I	Fluence and dose equivalent in specific energy bins for unfolded neutron spectra, run 29/8/90 (APØ).
Table II	Fluence and dose equivalent in specific energy bins for unfolded neutron spectra, run 31/8/90 (APØ).
Table III	Fluence and dose equivalent in specific energy bins for unfolded neutron spectra, in the Linac tunnel.

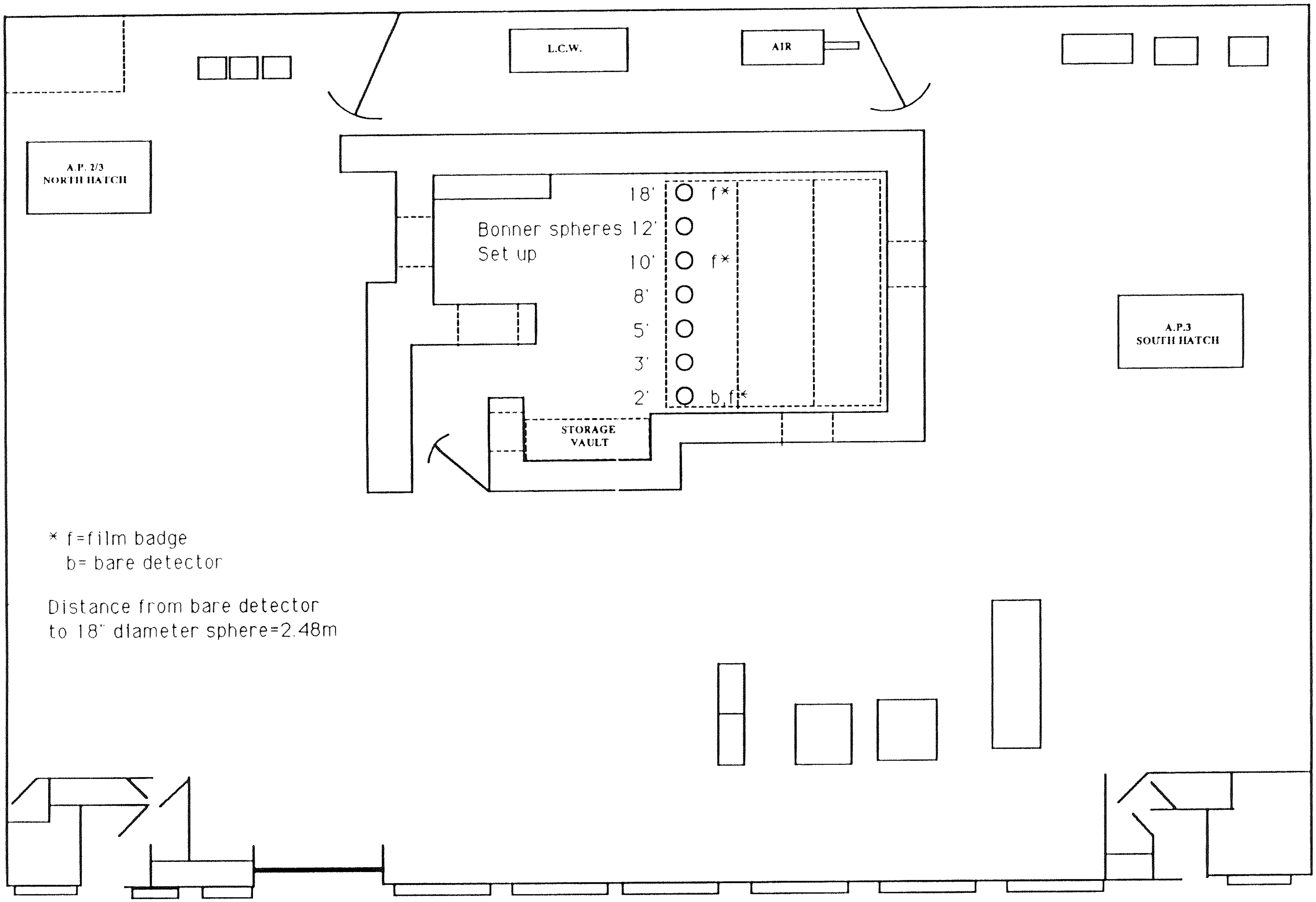
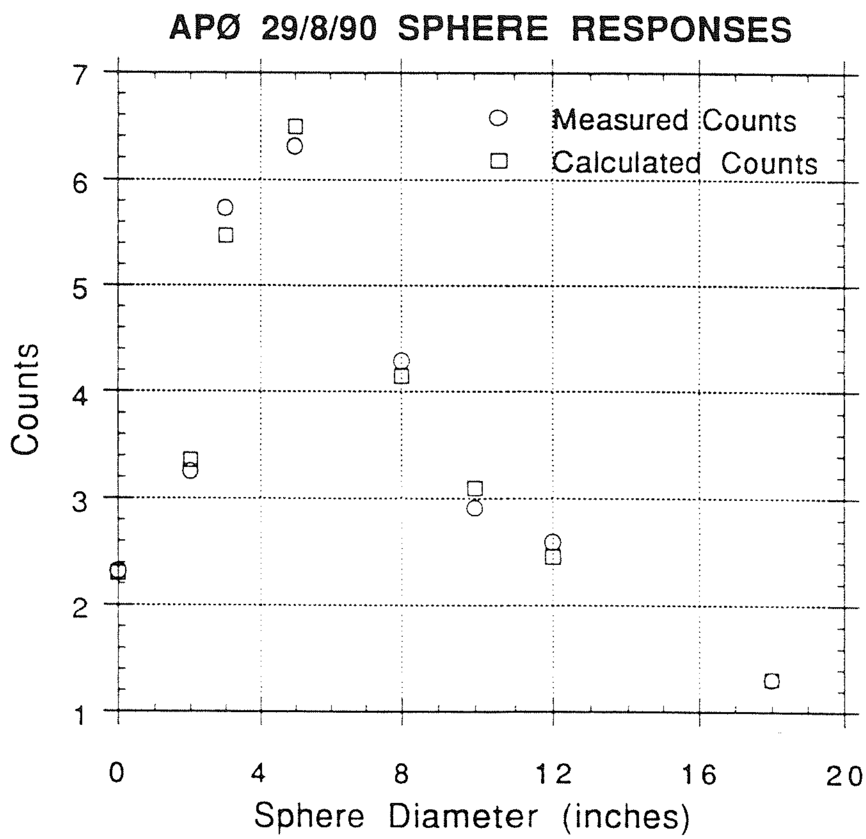


Figure 1. Anti-Proton Target Building (APØ).

Figure 2. Sphere Responses as a function of diameter, APØ run, measured results are compared with the one from spectrum unfolding using Bunki code.



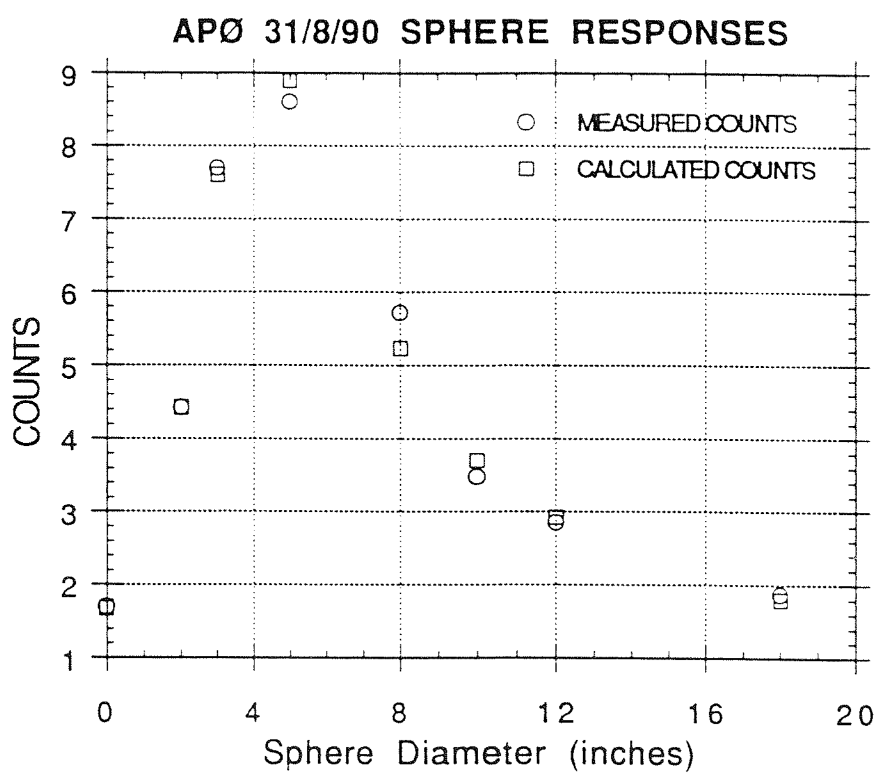
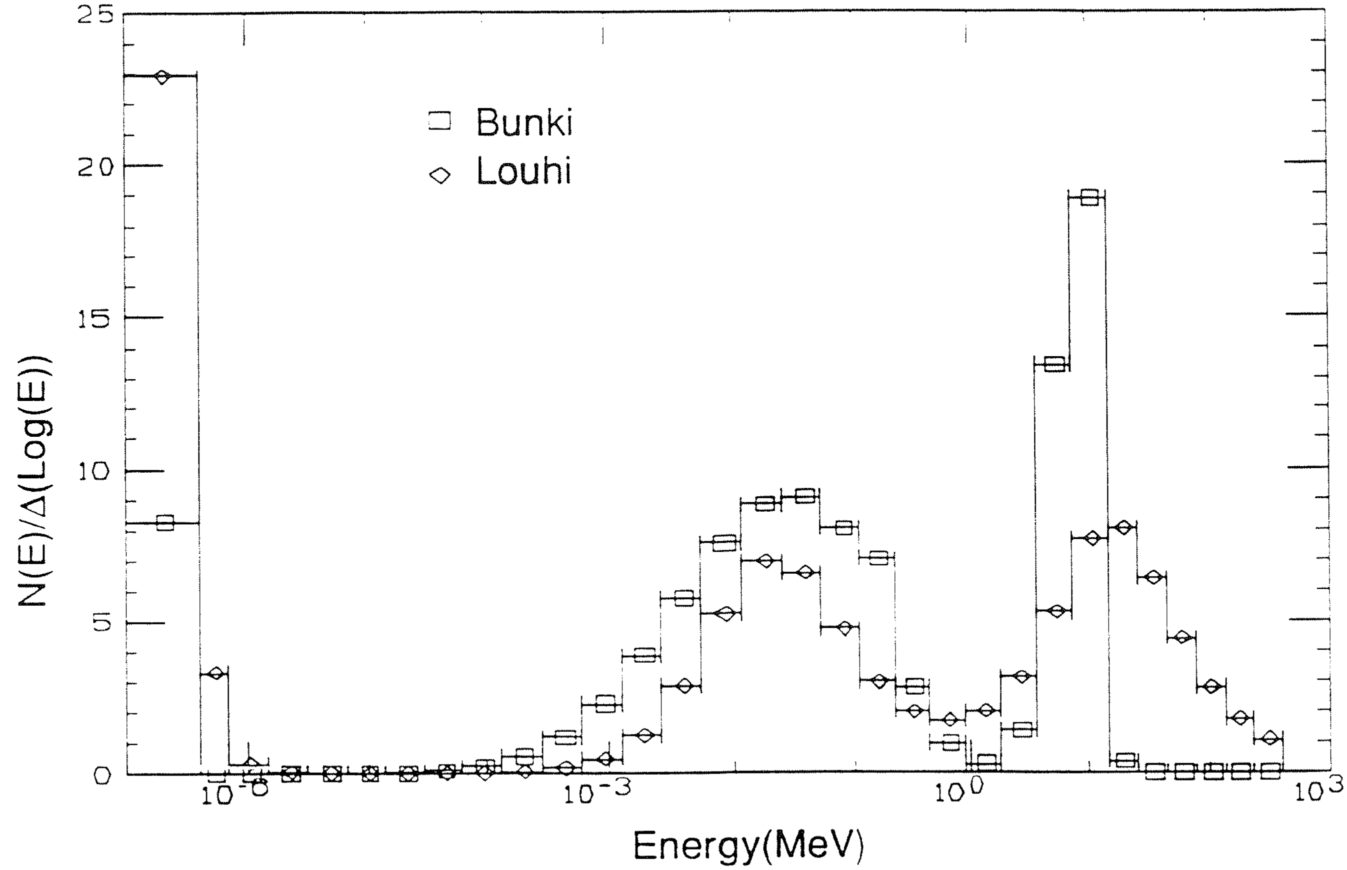


Figure 3

APø 29/8/90 TARGET VAULT



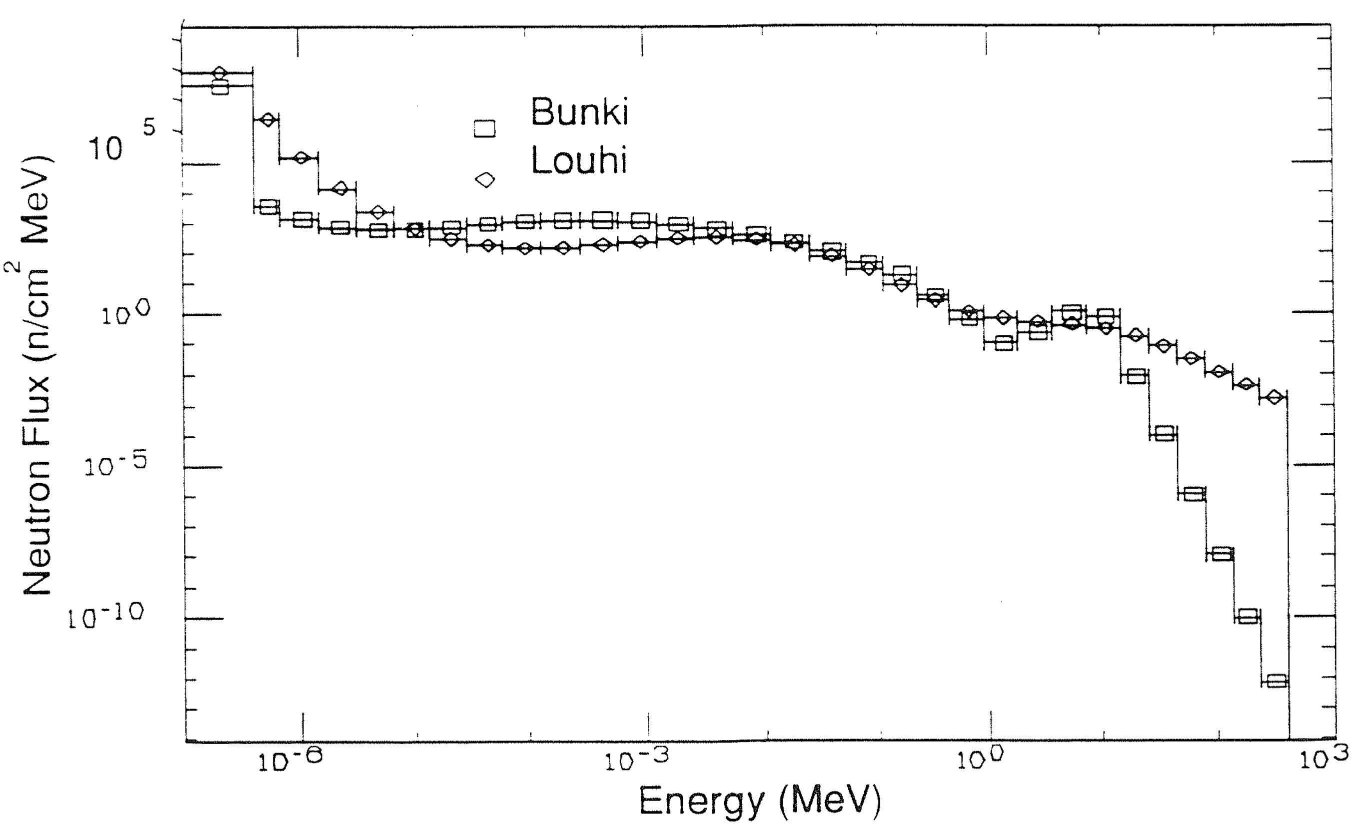
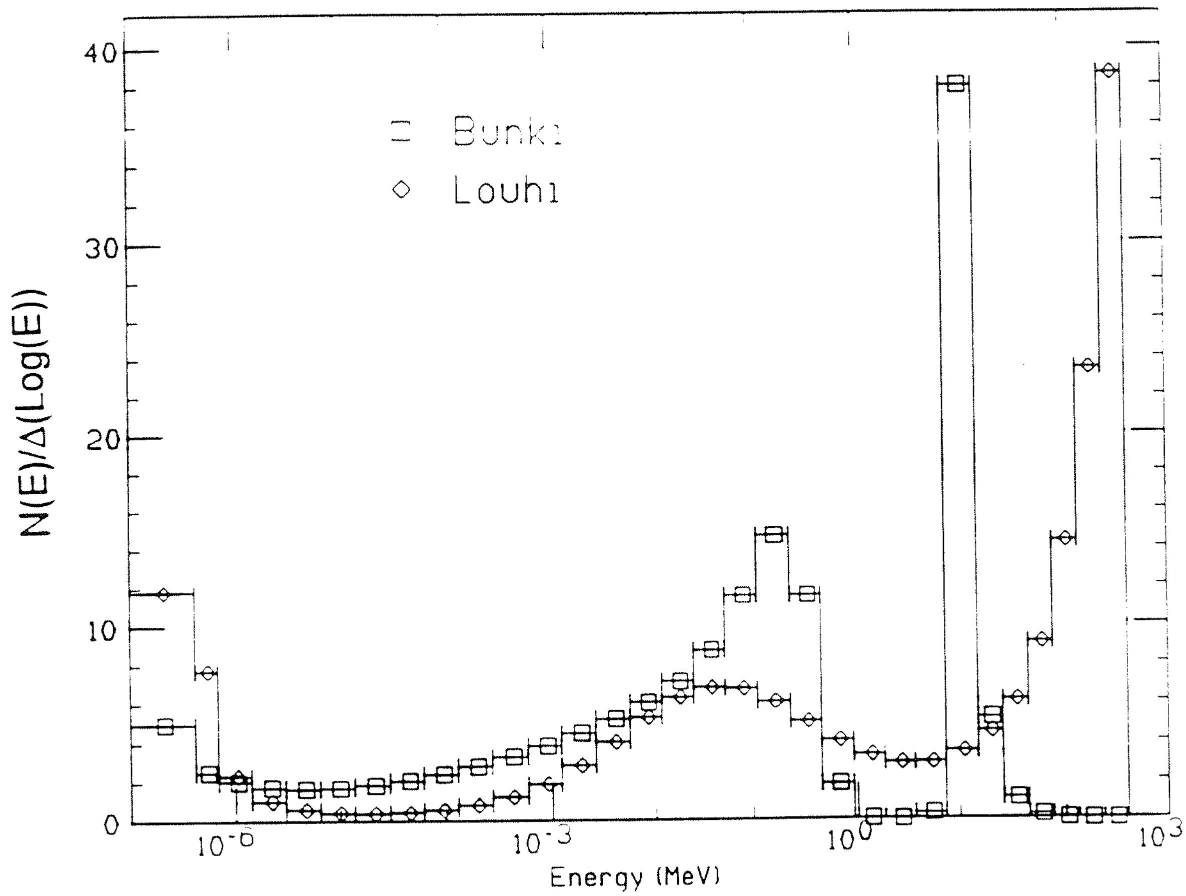


Figure 4

APO 31/8/90 TARGET VAULT



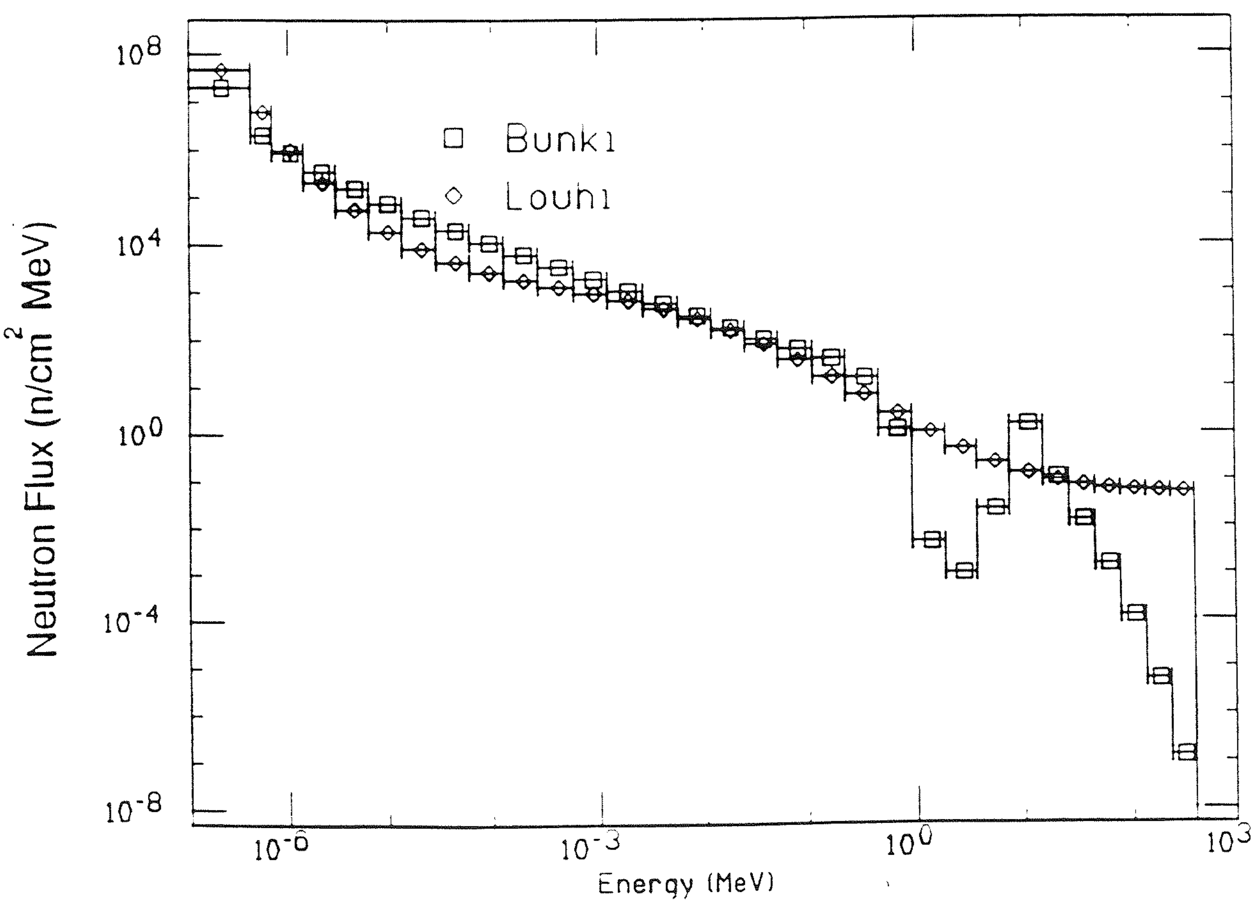


Figure 5. The Bonner Sphere Set up at the Linac Tunnel.

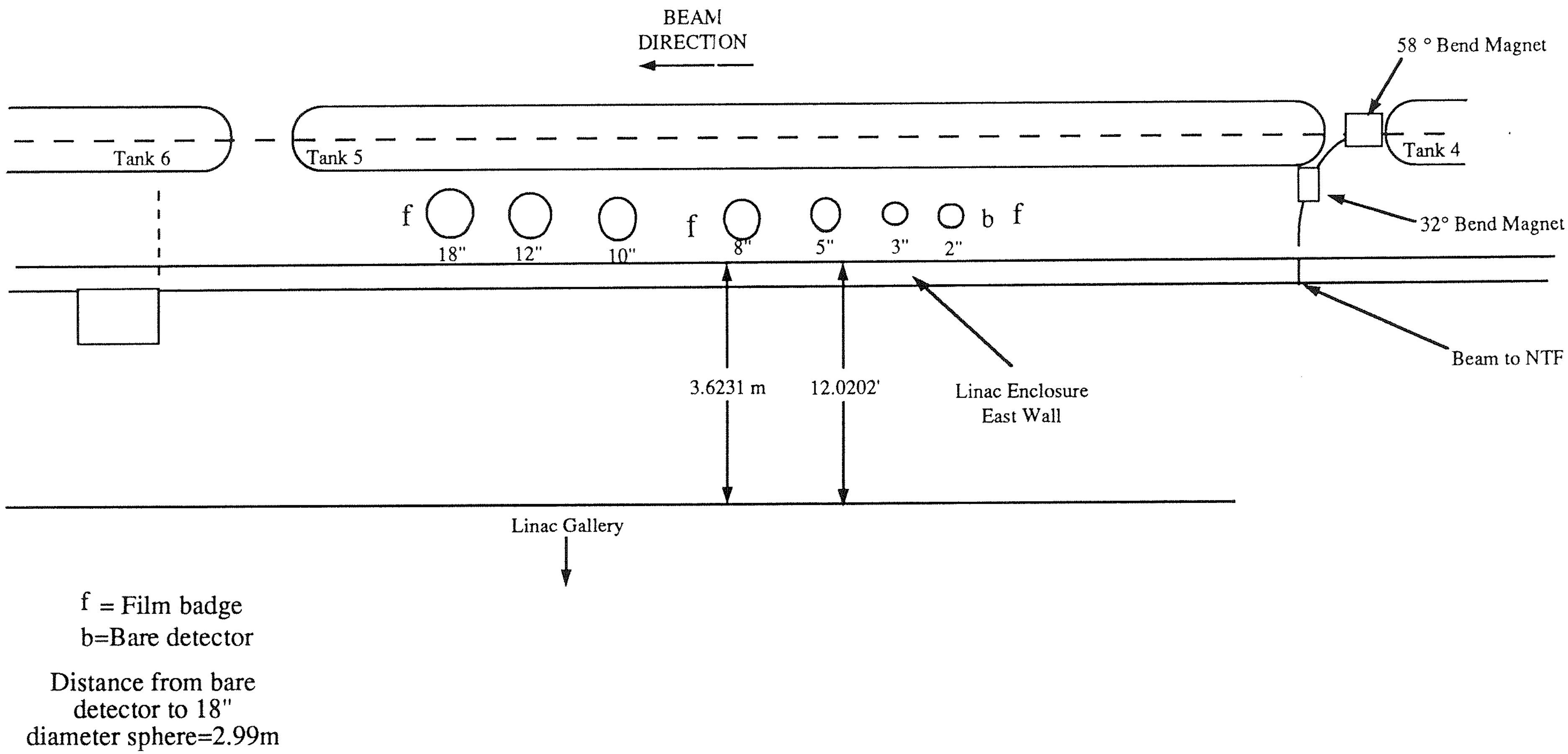
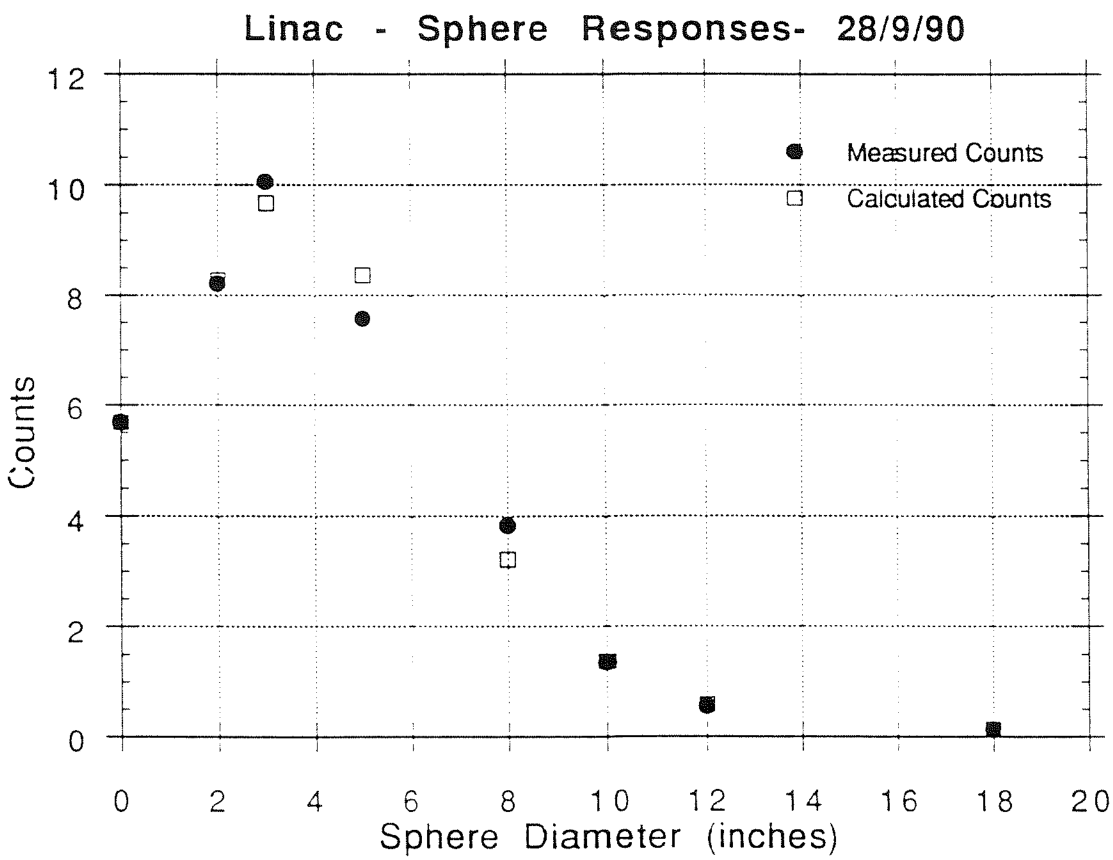


Figure 6. Measured sphere responses compared to those based on unfolding with Bunki code, in the Linac tunnel.



Linac 28/9/90 Figure 7.

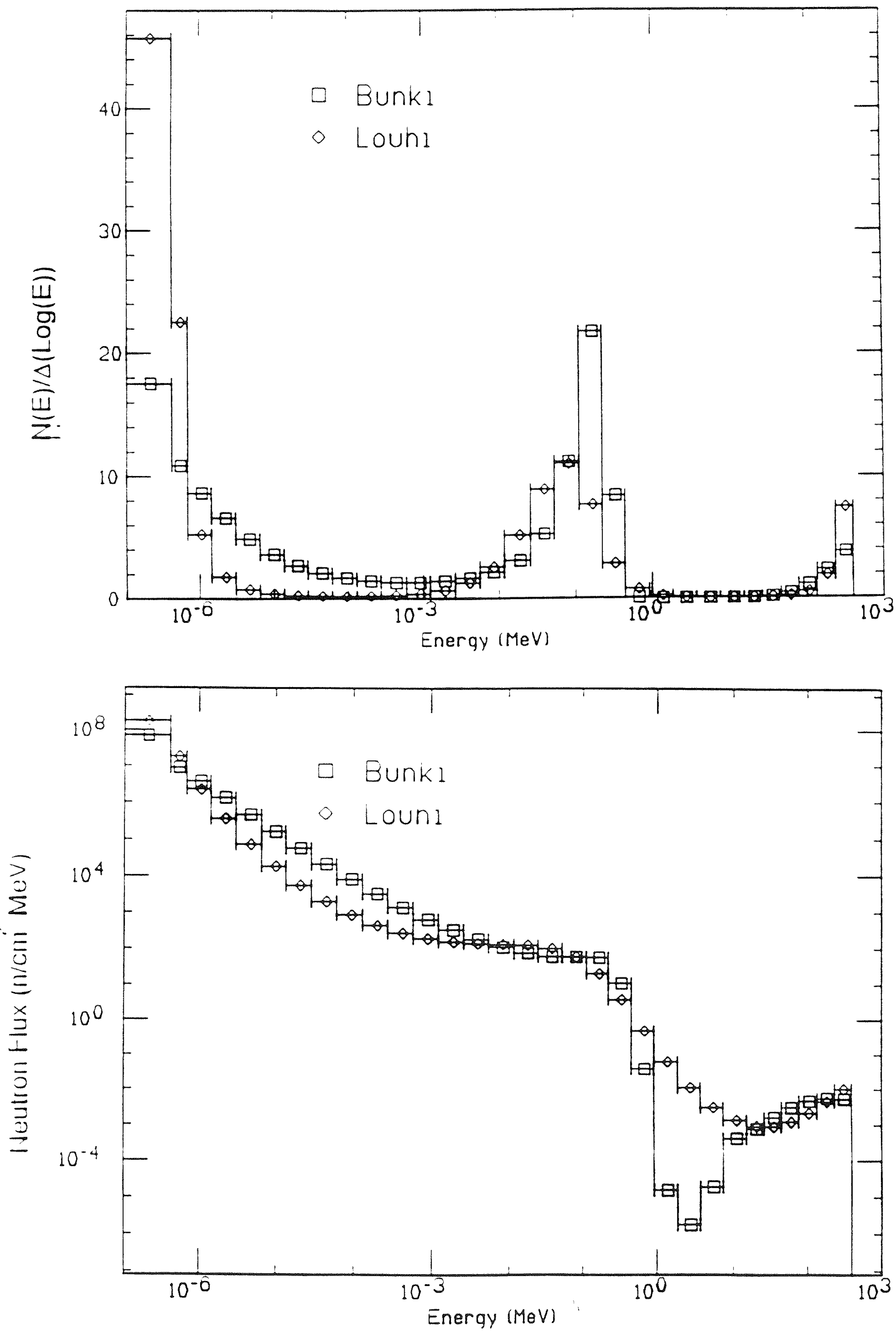


Table I

Fluence and Dose Equivalent in Specific Energy Bins for Unfolded Neutron Spectra
(in percentage of total fluence and dose equivalent at given position)
APØ 29/8/90

Bin Range	Fluence 29/8/90 (Bunki)	Fluence 29/8/90 (Louhi)	Dose Equiv. 29/8/90 (Bunki)	Dose Equiv. 29/8/90 (Louhi)
< 1.5 eV	31.5	30	3.1	2
1.5 eV - 0.1 MeV	50.3	31	6.3	6
0.1 MeV - 2.0 MeV	7.9	9	7.9	12
2 MeV - 25 MeV	10.3	20.6	82.7	52
> 25 MeV	-	9.4	-	28
Quality Factor	-	-	6.0	5.7

Table II

Fluence and Dose Equilavent in Energy Bins for Unfolded Neutron Spectra
(in percentage of total fluence and dose equivalent at given position)
APØ 31/8/90

Bin Range	Fluence 31/8/90 (Bunki)	Fluence 31/8/90 (Louhi)	Dose Equiv. 31/8/90 (Bunki)	Dose Equiv. 31/8/90 (Louhi)
< 1.5 eV	16.6	15	1.4	1
1.5 eV - 0.1 MeV	41.5	32	6.2	3
0.1 MeV - 2.0 MeV	16.5	13	14.3	11
2 MeV - 25 MeV	24.8	8	76.1	14
> 25 MeV	0.6	31	2.0	71
Quality Factor	-	-	5.8	4.4

Table III

Linac Tunnel

Fluence and Dose Equivalent in Specific Energy Bins for Unfolded Neutron Spectra
(in percentage of total fluence and dose equiv. at given position)

Bin Range	Fluence 28/9/90 (Bunki)	Fluence 28/9/90 (Louhi)	Dose Equiv. 28/9/90 (Bunki)	Dose Equiv. 28/9/90 (Louhi)
< 1.5 eV	50.3	57	13	15
1.5 eV - 0.1 MeV	33	33.3	35	25
0.1 MeV - 2.0 MeV	15	6.7	33.4	21
2 MeV - 25 MeV	0.02	0.1	0.2	2
> 25 MeV	1.6	2.9	18.4	37
Quality Factor	-	-	4.0	3.9